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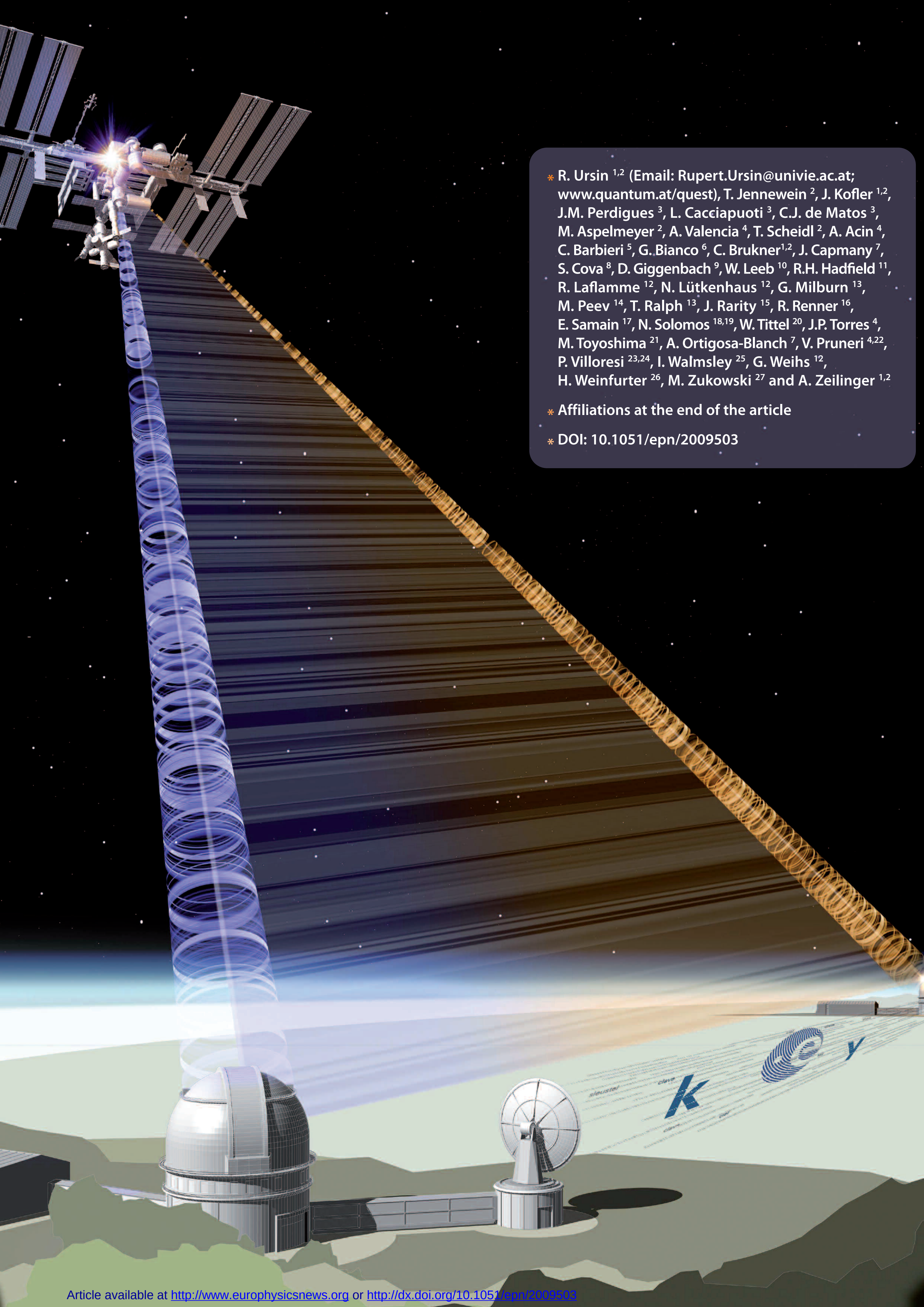

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SPACE-QUEST

EXPERIMENTS WITH QUANTUM ENTANGLEMENT IN SPACE

Quantum entanglement is, according to Erwin Schrödinger in 1935 [1], the essence of quantum physics. It inspires fundamental questions about the principles of nature. By testing the entanglement of particles, we are able to ask fundamental questions about realism and locality in nature [2]. Local realism imposes certain constraints in statistical correlations of measurements on multi-particle systems. Quantum mechanics, however, predicts that entangled systems have much stronger than classical correlations that are independent of the distance between the particles and are not explicable with classical physics.

It is an open issue whether quantum laws, originally established to describe nature at the microscopic level of atoms, are also valid in the macroscopic domain such as long distances. Various proposals predict that quantum entanglement is limited to certain mass and length scales or is altered under specific gravitational circumstances.

Testing the quantum correlations over distances achievable with systems placed in the Earth orbit or even beyond would allow verifying both the validity of quantum physics and the preservation of entanglement over distances impossible to achieve on ground. Using the large relative velocity of two orbiting satellites, one can perform experiments on entanglement where – due to special relativity – both observers can claim that they have performed the measurement on their system prior to the measurement of the other observer. In such an experiment it is no longer possible to think of any local realistic mechanisms that potentially influence one measurement outcome according to the other one.

Moreover, quantum mechanics is also the basis for emerging technologies of quantum information science, presently one of the most active research fields in physics. Today's most prominent application is quantum key distribution (QKD) [3], *i.e.* the generation of a provably unconditionally secure key at distance, which is not possible with classical cryptography. The use of satellites allows for demonstrations of quantum communication on a global scale, a task impossible on ground with current optical fiber and photon-detector technology. Currently, quantum communication on ground is limited to the order of 200 kilometers [4]. Bringing quantum communication into space is the only way to overcome this limit with state-of-the-art technology.

Another area of applications is metrology, where quantum clock synchronization and quantum positioning [5] are studied. Furthermore, sources of quantum states in space may have applications in the new field of quantum astronomy.

◄ FIG. 1: Distribution of pairs of entangled photons using the International Space Station (ISS). Entangled photon pairs are simultaneously distributed to two separated locations on Earth, thus enabling both fundamental quantum physics experiments and novel applications such as quantum key distribution. (Image courtesy ESA/GSRP

The proposed experiments

We propose to ESA to perform these experiments in space by placing a quantum transceiver on the external pallet of the European Columbus module at the ISS (see Fig. 1). The entire terminal must not exceed the specifications given for pallet payloads as provided by ESA. The requirements are: size $1.39\times1.17\times0.86$ m^3, mass < 100 kg, and a peak power consumption of < 250 W, respectively. A preliminary design of a satellite-based quantum transceiver (including an entangled photon source, a weak pulse laser source, single photon detection modules together with two transceiver telescopes) based on state-of-the-art optical communication terminals and adapted to the needs of quantum communication has already been published in [6] (see Fig. 2).

The entangled photons are transmitted to two distant ground stations via simultaneous down-links [7], allowing a test on entanglement and the generation of an unconditional secure quantum cryptographic key between stations separated by more than 1000 km. ▪▪▪

Additionally, such a quantum transceiver in space is capable of performing two consecutive single down-links—using the entangled or the weak pulse laser onboard the satellite—establishing two different secure keys between the satellite and each of the ground stations (say, Vienna and Tokyo). Then a logical combination of the two keys (*e.g.* bitwise XOR) is sent publicly to one of the two ground stations. Out of that, an unconditionally secure key between the two ground stations can be computed. Using such a scheme would allow for the first demonstration of global quantum key distribution.

An important step towards the applicability of quantum communication on a global scale is to extend single QKD links to a quantum network by key relaying along a chain of trusted nodes using satellites as well as fiber-based systems. Furthermore, the efficiency of quantum networks can be improved employing quantum percolation protocols [8].

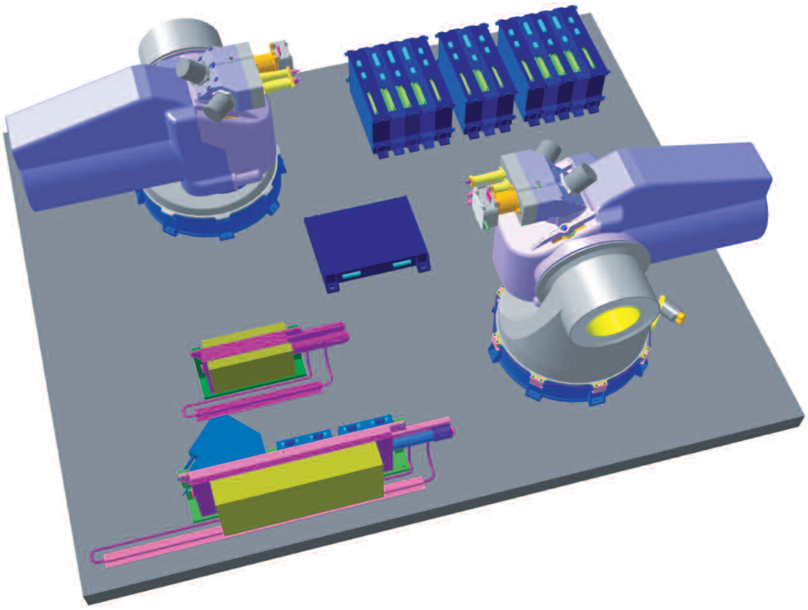
It would be favorable to include in parallel to the QKD down-link from the ISS a high-speed communication link providing several Gigabit per second bandwidth [9].

Proof-of-principle experiments

As an important step towards quantum communication protocols using satellites various proof-of principle demonstrations of quantum communication protocols have already been performed over terrestrial free-space links. One experiment was carried out on the Canary Islands using a 144 km free-space link, between the neighboring islands La Palma and Tenerife (Spain), where ESA's 1-meter-diameter receiver telescope, originally designed for classical laser communication with satellites, was used [10, 11] to receive single photons (see Fig. 3).

In a second experiment the Matera-Laser-Ranging-Observatory (Italy) was used to establish a single photon downlink from a low-earth orbit satellite [12]. A satellite-to-Earth quantum-channel down-link was simulated by reflecting attenuated laser pulses off the optical retro-reflector on board the satellite Ajisai, whose orbit has a perigee height of 1485 km.

An important component in space-based quantum communication is a source for entangled photons that is suitable for space applications in terms of efficiency, mass and power consumption. A source fulfilling the payload requirements based on highly efficient down-conversion crystals which deliver the necessary numbers of photon pairs has been published in [13].



▼ **FIG. 2:** Image of the preliminary design of a transceiver suitable for the external pallet of the European Columbus module at the ISS. The terminal contains a source for entangled photons as well as for decoy laser pulses, the onboard electronics and two transmitter telescopes. (Image courtesy Oerlikon.)

Topical team

In 2007, the formation of a Topical Team for supporting the Space-QUEST experiment comprised of researchers from academia actively involved in relevant scientific fields was initiated by ESA and currently consists of 38 members from 10 countries. This team will support the proposal with their individual scientific and technical expertise and also aims to increase the research community's interaction with industry. The present programmatic roadmap of Space-QUEST is compatible with a launch date by end of 2014 [14,15].

Conclusions

We emphasize that the space environment will allow quantum physics experiments with photonic entanglement and single photon quantum states to be performed on a large, even global, scale. The Space-QUEST proposal aims to place a quantum communication transceiver containing the entangled photon source, a weak pulsed (decoy) laser source and single photon counting modules in space and will accomplish the first-ever demonstration in space of fundamental tests on quantum physics and quantum-based telecom applications. The unique features of space offer extremely long propagation paths to explore the limits of the validity of quantum physics principles. In particular, this system will allow for a test of quantum entanglement over a distance exceeding 1000 km, which is impossible on ground. &&■

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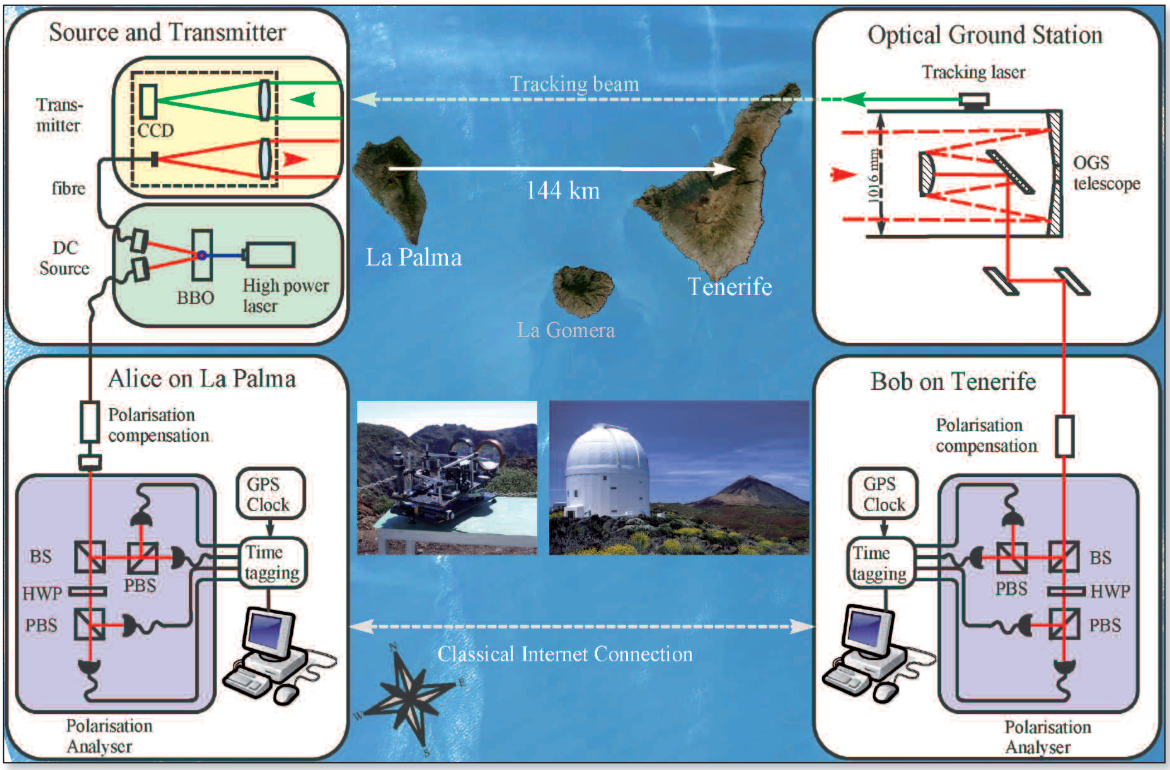

◄ **FIG. 3:** Proof-of-principle inter-island quantum communication experiment between the Canary Islands La Palma and Tenerife over a 144 km free-space link. The receiver on Tenerife was the Optical Ground Station of ESA, which contains a 1 m telescope. This system is used for optical communication with satellites, and was adapted as a quantum communication receiver (from Ref. [11]).

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